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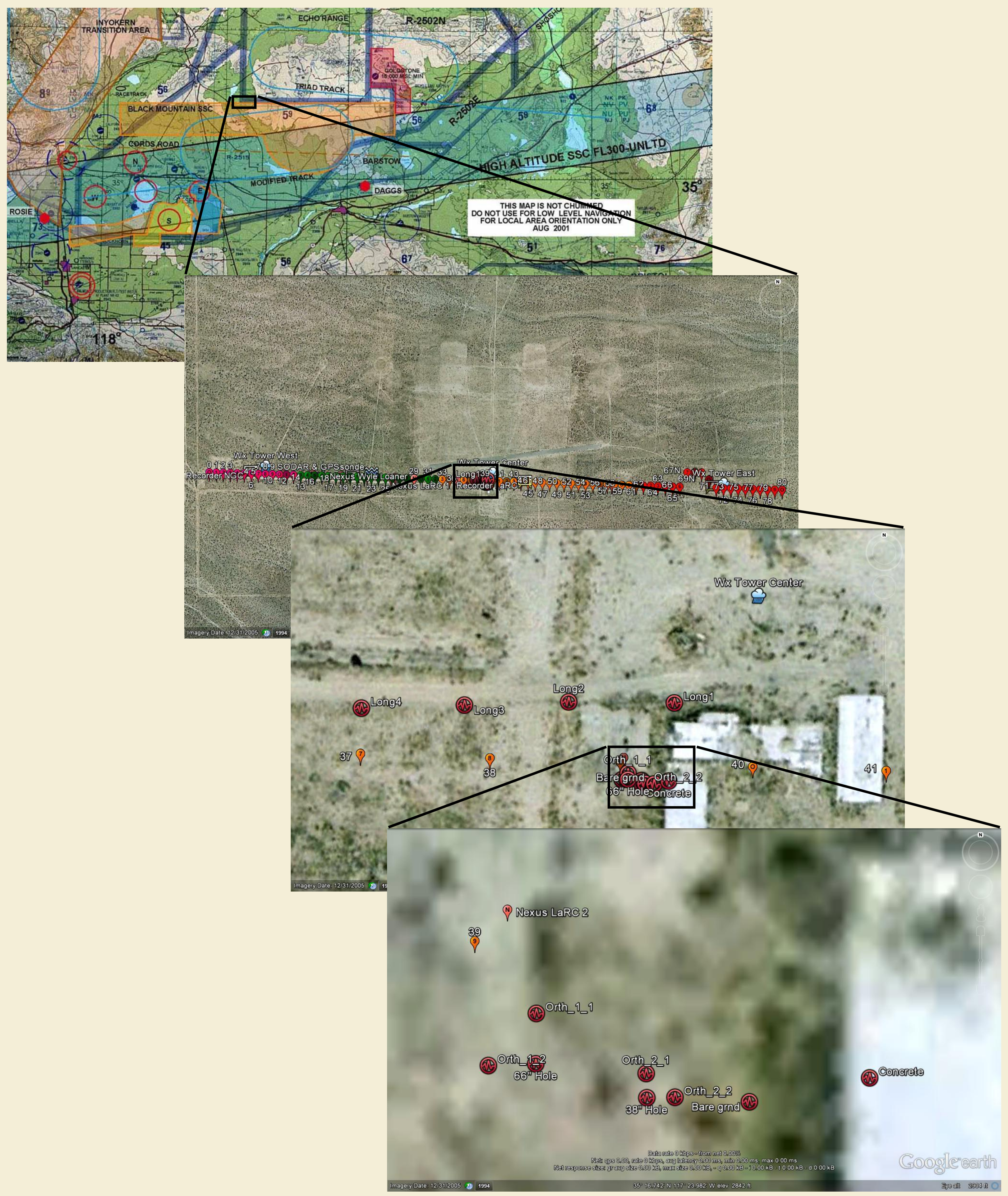
High Quality Observations of Sonic Booms

Gilead Wurman[1], Edward A. Haering, Jr.[2], and Michael J. Price[1]
[1]Seismic Warning Systems, Inc., Scotts Valley, CA; [2]NASA Dryden Flight Research Center, Edwards, CA

Background

The SonicBREWS project (Sonic Boom Resistant Earthquake Warning Systems) is a collaborative effort between Seismic Warning Systems, Inc. and NASA Dryden Flight Research Center. This project aims to evaluate the effects of sonic booms on Earthquake Warning Systems in order to prevent such systems from experiencing false alarms due to sonic booms. The airspace above the Antelope Valley, California includes the High Altitude Supersonic Corridor and the Black Mountain Supersonic Corridor. These corridors are among the few places in the US where supersonic flight is permitted, and sonic booms are commonplace in the region.

NASA conducts regular supersonic flight experiments in the vicinity of Edwards Air Force Base, and accelerometers were positioned to record during three of these experiments. The first, Sonic Booms on Big Structures (SonicBOBS), took place in the fall of 2010. This experiment generated 42 distinct sonic booms that were recorded in and around the Consolidated Services Facility, a large building at Edwards AFB. The second, the Superboom Caustic Analysis and Measurement Project (SCAMP) occurred in May 2011 near Cuddeback Dry Lake in the Mojave desert. This experiment generated 70 sonic booms, of which 37 were recorded by accelerometers. Finally, in October 2011 five sonic booms were recorded at Building 4800 on the NASA Dryden campus as part of the Waveform and Sonicboom Perception and Response (WSPR) experiment. In all, 74 designed sonic booms have been recorded to date, with at least 15 more in three dedicated SonicBREWS flights anticipated in the future.



Superboom Caustic Analysis and Measurement Project

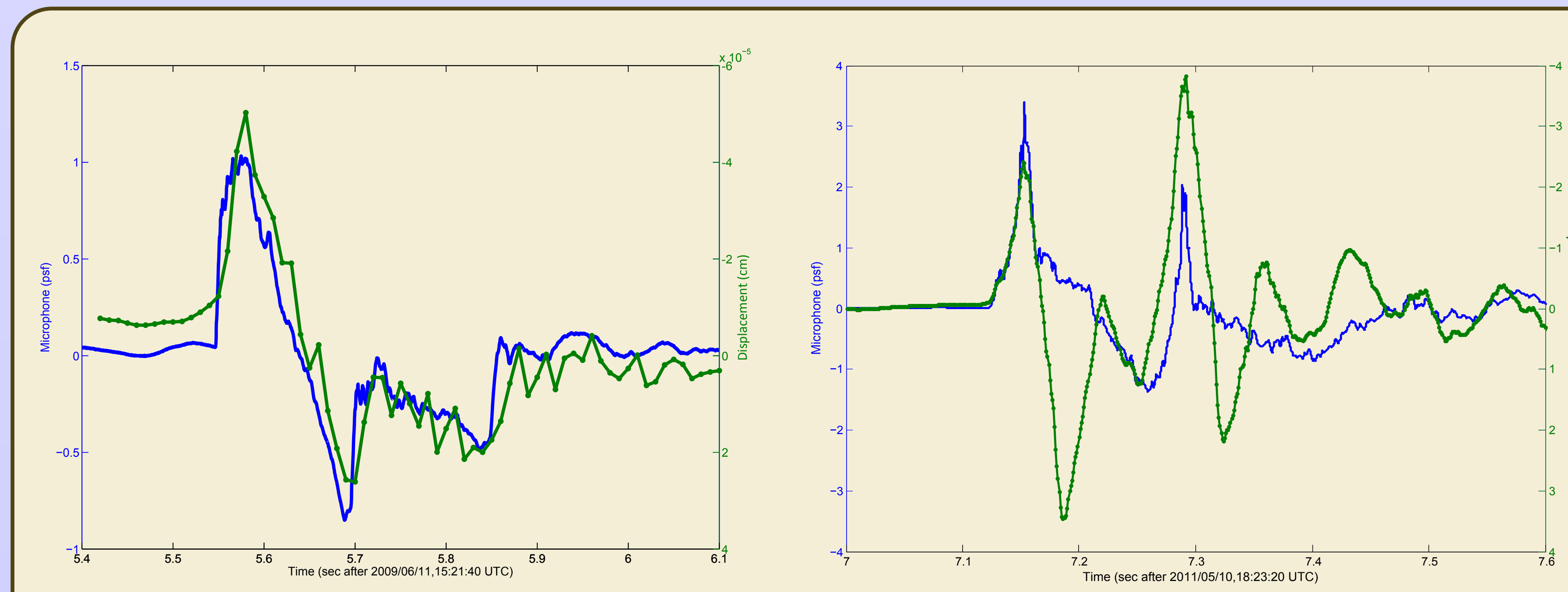
The Superboom Caustic Analysis and Measurement Project (SCAMP) is a NASA project designed to characterize the spatial evolution of a sonic boom head wave (or caustic) along a 3 km array of microphones. The experiment was set up near the Cuddeback Dry Lake in the Antelope Valley, beneath the northern edge of the Black Mountain Supersonic Corridor. Over the course of two weeks, NASA F-18 research aircraft performed supersonic passes over the array, generating 70 sonic booms in total.

Over the course of this experiment, four high-rate accelerometers were deployed in various array configurations. Of the 70 sonic booms generated for the experiment, the accelerometers successfully recorded 37 (accelerometers were not deployed on all days). One configuration was a longitudinal array with 30 m separation between the sensors. Another two were orthogonal arrays with baseline lengths of 38 in. and 66 in., including boreholes of equal depth. In one configuration, each sensor was sited in different conditions: one in a 66 in. hole, one in a 38 in. hole, a third on the natural desert surface, and the fourth on the concrete foundation of a demolished building. This array produced data on the response of the ground to the sonic boom.

Surface Response to Pressure Wave

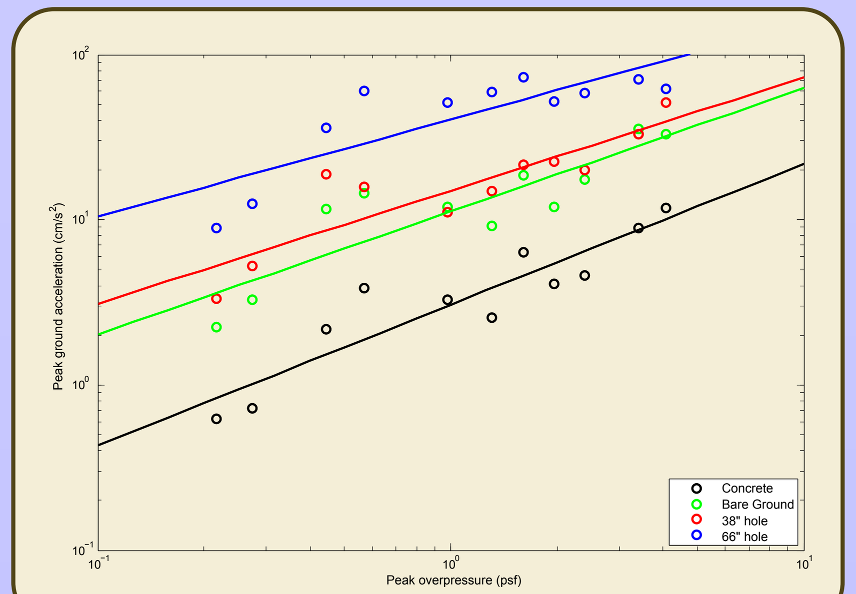
Sonic booms from space shuttle re-entry are readily detectable on modern seismometers [*Kanamori et al.*, 1991; *Sorrell et al.*, 2002]. The figure on the left shows a record of a sonic boom from an F-18 at Edwards AFB. The blue trace is a microphone in the free field, and the green trace is the vertical displacement from nearby CISN station EDW2. The displacement is integrated from velocity and inverted to overlay with the microphone record. The initial sonic boom phase, the N-wave, has a characteristic shape which is easily discernible in displacement when integrated from velocity.

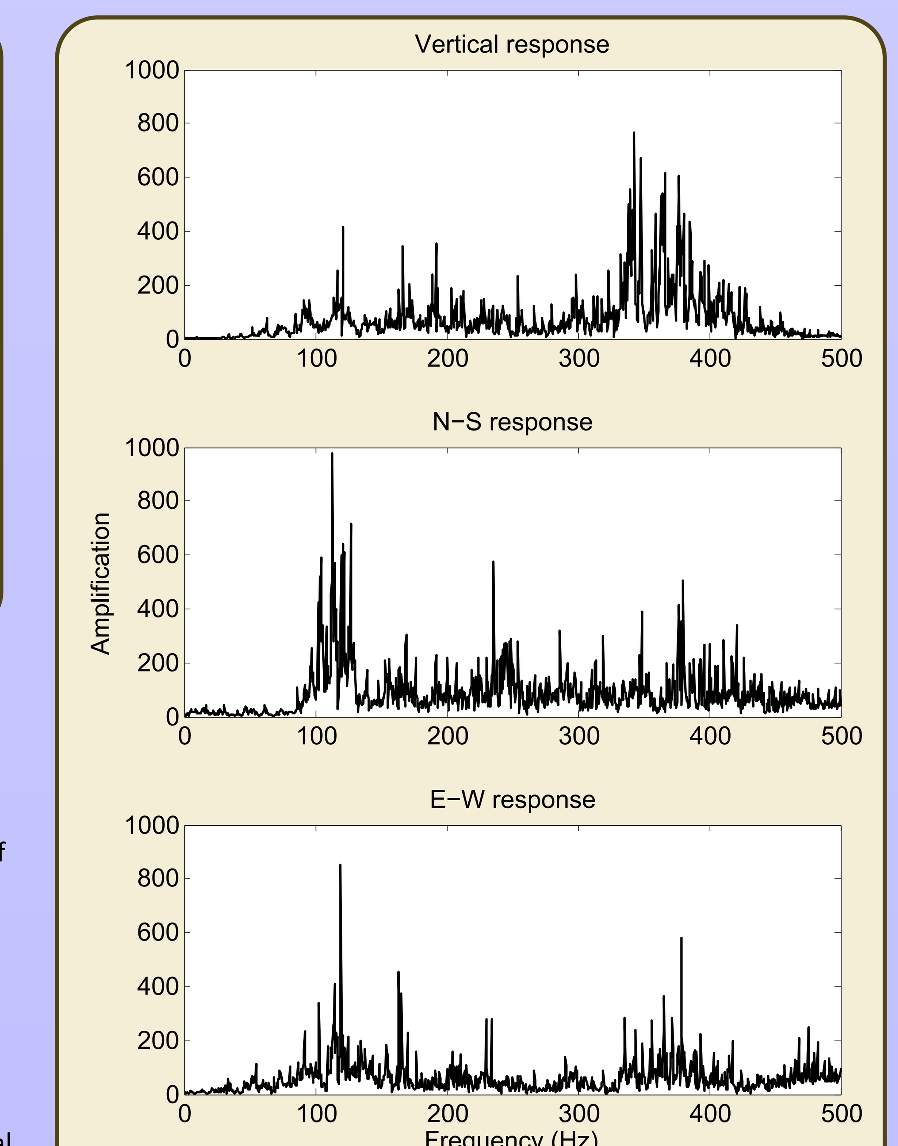
The figure on the right shows a sonic boom recorded on the SCAMP array. Again the blue trace is a microphone record. The green trace is recorded by an accelerometer resting on the desert surface. The record has to be double-integrated to arrive at displacement, and this process reduces the fidelity of the ground motion record. As a result the seismic record does not mirror the microphone record as closely as when recorded on a velocity sensor.



We drilled two boreholes for the SCAMP experiment in an effort to find a depth at which a sensor could be mounted, such that the seismic signature of the sonic boom will have attenuated enough to neglect. This turned out to be counter-productive. As seen in the figure below left, siting the accelerometer at the bottom of a 38" hole (red data) had a negligible effect on peak ground accelerations relative to bare ground (green data). In fact, recordings from a sensor mounted at the bottom of a 66" hole (blue data) exhibit an amplification over bare ground by around a factor of 5. We suspect this is actually due to the pressure wave resonating in the column of the deeper hole. However, we were unable to eliminate the effect by plugging the top of the borehole with foam.

An interesting result is that the sensor resting on the concrete slab (black data) exhibited a factor of 5 lower ground motions than the adjacent bare ground sensor. This is counterintuitive in that we expected the slab to behave roughly like a sail, and respond coherently to the pressure over its entire surface. However, the pressure wave does not strike the entire slab simultaneously, but rather propagates across it over the course of ~40 ms. As a result, we suspect the slab's rigidity actually acts to attenuate its vertical deflection rather than amplifying it.

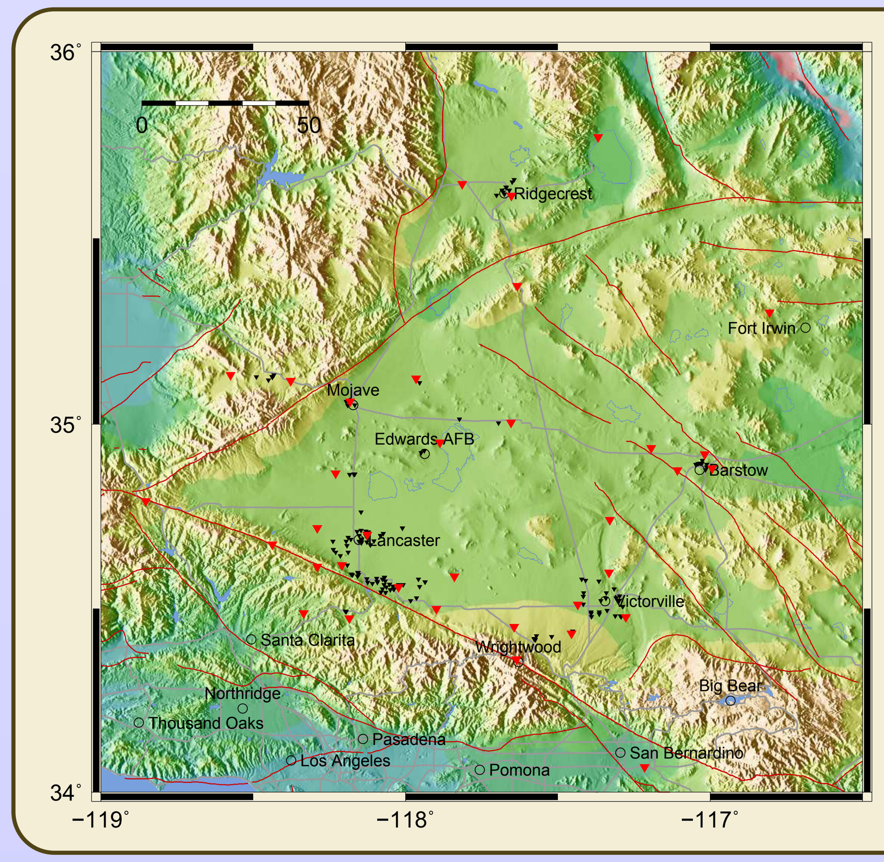




In a separate set of booms as part of the WSPR experiment, we instrumented Building 4800 on the NASA Dryden campus with two accelerometers on the foundation and two accelerometers on the roof directly above the lower pair. The figure at right shows the spectral ratios of the vertical and horizontal components of the roof sensors to the basement sensors.

Because sonic booms are dominated by much higher frequencies than earthquakes, building response is best illuminated at frequencies over 50 Hz. The building shows significant amplification in the horizontal channels between 75 and 150 Hz, while the amplification in the vertical channel is predominantly in the 300-400 Hz range.

Implications for Earthquake Warning Systems



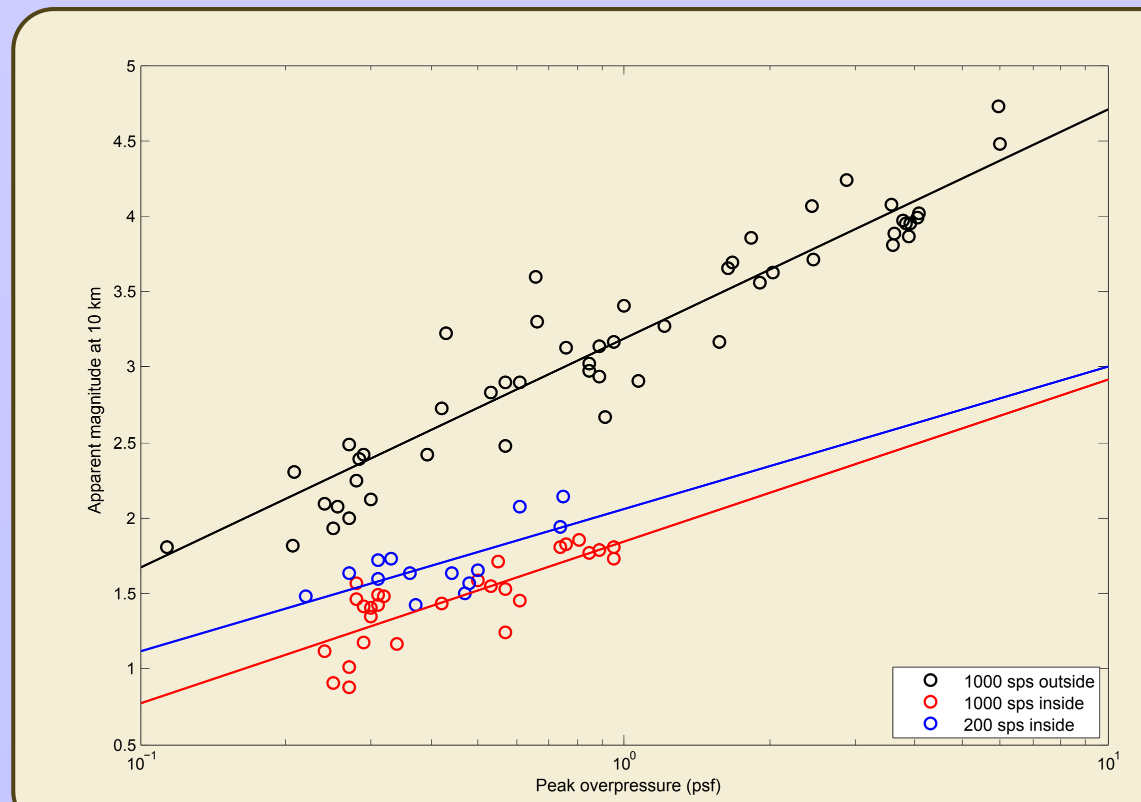
Seismic Warning Systems and NASA Dryden intend to collaborate on establishing a regional Earthquake Warning System (EWS) for the Antelope Valley. The map above outlines the proposed deployment. Red triangles represent potential seismometer sites, and the smaller black triangles represent all the public schools in the region as well as several government properties which would be protected by the regional system.

Because of the nature of flight activities in the Antelope Valley, the proposed EWS needs to be protected against false positives due to sonic booms. Part of the purpose of these tests is to determine whether the booms produce ground motions comparable to the P-wave from an earthquake of significant size. To determine this, we integrate the acceleration record to velocity and take the relation from Wurman et al. [2007] for magnitude as a function of peak P-wave velocity:

$$M = 1.63\ \mathrm{Log}_{10}(PGV) + 4.40\ \mathrm{Log}_{10}(R) + 1.65$$

where R is the epicentral distance. We set this distance to 10 km as a reference to determine if an EQW system based on peak displacement algorithms can be spoofed by a sonic boom under realistic conditions. We find that sonic booms approaching 10 psf overpressure can generate ground velocities comparable to a M 5 at 10 km distance. However, a 10 psf boom is fairly extreme; the typical overpressure from the re-entry of the space shuttle was less than about 2.5 psf [*Garcia et al.*, 1985]. This value corresponds to slightly less than a M 4 at 10 km.

In addition, we observed during the SonicBOBS experiment that sensors positioned inside a building experience significantly attenuated accelerations (blue and red data below). We also note that, due to the high-frequency content of the sonic booms, a lower sample rate (200 sps, in blue) significantly aliases the record, leading to artificially increased peak velocity values.



Conclusions

We have to date recorded 74 sonic booms with high rate accelerometers recording up to 1000 samples per second. At least 15 more booms are scheduled before the conclusion of the project. The dataset includes sonic booms ranging from 0.1 to 10 psf overpressures recorded with various array configurations. These records will help determine the best means for hardening an Earthquake Warning System against false positives from sonic booms.

References

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